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PALEOMAGNETISM OF JURASSIC ROCKS IN THE WESTERN SIERRA NEVADA METAMORPHIC BELT AND ITS BEARING ON THE STRUCTURAL EVOLUTION OF THE SIERRA NEVADA BLOCK

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Abstract. The western metamorphic belt of the Sierra Nevada consists of two eugeosynclinal terranes separated by the Melones and Sonora faults. Subvertical, bedded Mesozoic volcanic rocks metamorphosed to low greenschist facies predominate to the west, whereas Paleozoic metamorphic rocks of higher grade and greater structural complexity predominate to the east. In order to study the structural development of the faults, 121 samples of basalt and diabase were collected for paleomagnetic analysis from three Jurassic formations, the Logtown Ridge and Penon Blanco formations west of the Melones fault and the Sonora dike swarm to the east of the Sonora fault. A northwesterly, downward directed magnetization occurs in each unit. Three fold tests and a conglomerate test on the two formations west of the faults show that the magnetization is secondary, postdating Nevadan (Late Jurassic) folding and is probably coeval with peak metamorphism. An average of five paleomagnetic poles from the Sierra Nevada, three derived from the secondary magnetizations given herein and two previously published, all of probable Kimmeridgian age, yields λ'=67.2°N, ϕ'=161.2°E, and α_{95}=6.5°. Southeasterly magnetizations also occur in the Logtown Ridge Formation and Sonora dike swarm. Directions from the Sonora dikes are approximately antipodal to the secondary directions and are reversed; magnetizations from the Logtown Ridge Formation yield similar results only if corrected for the tilt of bedding. The Logtown Ridge magnetizations (tilt-corrected) yield a pole position near to that expected for North America. The data from the Sonora dikes require a tilt correction of 25°-30° toward the south-southwest about a horizontal axis parallel to the regional structure in order to yeild a North American pole position. We conlude that the eastern wall rocks of the Melones and Sonora faults have been rotated 25°-30° in response to Nevadan deformation in contrast to the western wall rocks, which have been rotated about 90°.

Introduction

Paleomagnetism is a powerful tool for determining the rotational component of deformation on scales ranging from the local to the regional [e.g., Van der Voo and Channell, 1980]. Many paleomagnetic studies have documented anomalies in paleodeclination, which commonly indicate rotations about vertical or near-vertical axes [e.g., Norris and Black, 1961; Van der Voo, 1969; Beck, 1976; Simpson and Cox, 1977; Luyendyk et al., 1980; etc.]. In most of these investigations, rotation was not suspected prior to the study because such deformation rarely has any clear-cut geologic expression other than aberrant paleodeclinations.

Rotations about horizontal or subhorizontal axes (tilts), however, are not commonly determined from paleomagnetic data. Other geologic markers, such as bedding, indicate tilts (due to folding or faulting), and these markers are usually used to correct paleomagnetic data or for the classic fold test [Graham, 1949] rather than to elucidate deformation. Where such markers are lacking, however, paleomagnetic data may be used to determine the extent of tectonic tilting [MacDonald, 1980]. Geissman et al. [1982], for example, used paleomagnetic data from Mesozoic basement rocks in the eastern Basin and Range province to document tilts greater than those shown by the stratified Cenozoic cover. Along continental margins, however, paleoinclination anomalies may be the result of either tilting due to folding or faulting or large-scale north-south transport. This ambiguity may or may not be resolved by considering the geologic context of units from which the aberrant data were obtained. In addition, sequential rotations about multiple axes may well have occurred in regions of continental margin orogenesis where polyphase deformation is common [MacDonald, 1980].

The western belt of the Sierra Nevada (Figure 1) is one such orogenic region where both single-phase and polyphase deformation have occurred [Taliaferro, 1942; Clark, 1964, 1976; Schweickert et al., 1984]. A prominent fault system, consisting of the Melones and Sonora faults, transects the region from north-northwest to south-southeast (Figure 1). The faults also divide the belt into a western part where deformation is relatively simple and has occurred largely during a single phase, and an eastern part, where deformation has been more complex with multiple phases locally. The major tectonic eposide, which has affected the entire region to a greater or lesser extent, is the Late Jurassic Nevadan orogeny [Schweickert et al., 1984]. In the course of a structural study of the Nevadan orogen and more specifically of the Melones and Sonora faults, we collected samples for paleo-

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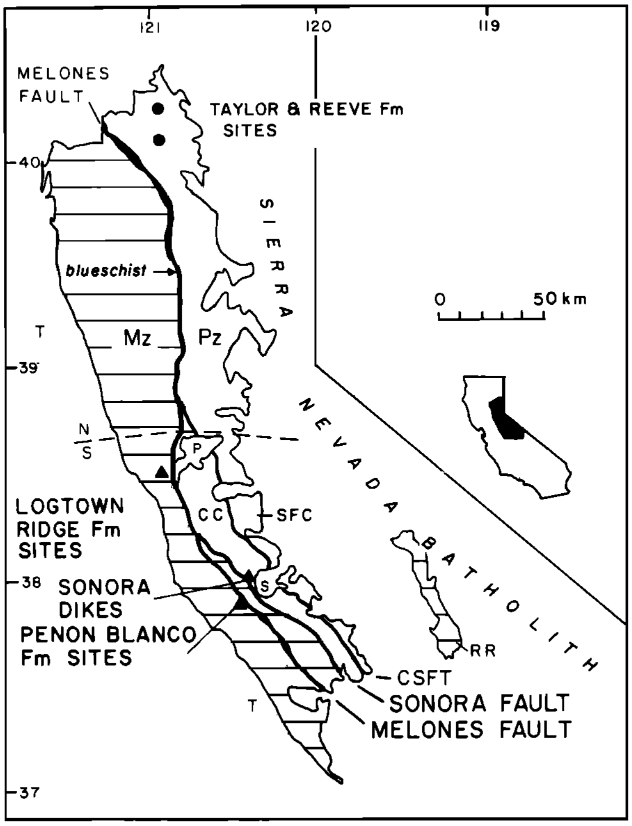

Fig. 1. Geologic relations in the western metamorphic belt of the Sierra Nevada of California. Triangles are the sites reported herein, and the circles are the localities of Hannah and Verosub [1980]. CC, SFC are the Calaveras and Shoo Fly Complexes, respectively, and CSFT is the Calaveras-Shoo Fly thrust. S, standard pluton; P, Plymouth pluton; T, Tertiary rocks; solid areas along the Melones fault are serpentinite bodies; Mz, Mesozoic rocks west of Melones and Sonora faults; Pz, Paleozoic rocks east of Melones and Sonora faults.

magnetic analysis from the wall rocks of the faults. These samples have yielded evidence of the magnitude of Late Jurassic and younger rotations in the western Sierra Nevada that have occurred about both vertical and horizontal axes.

Geologic Setting and Sampling Localities

The western metamorphic belt of the Sierra Nevada, defined by Clark [1964, 1976], consists of steeply dipping, pre-Cretaceous units between the Sierra Nevada batholith to the east and unconformably overlying Tertiary strata of the Great Valley to the west (Figure 1). The Melones fault north of latitude 38°15'N and the Sonora fault south of latitude 38°15'N strike north-northwest and divide the belt into two parts, one Mesozoic and the other Paleozoic [Clark, 1960, 1964, 1976; Schweickert, 1978, 1981; Schweickert et al., 1984]. Mesozoic, mainly Jurassic, volcanic, and intrusive rocks overlain by synorogenic flysch, the Marioposa Formation, predominate west of these faults. Metasedimentary and metavolcanic rocks of Paleozoic and probable Paleozoic age predominate in at least two tectonostratigraphic terranes to the east of the faults. All of the Paleozoic and Mesozoic rocks formed in eugeosynclinal, marine settings and all have been deformed and metamorphosed to varying degrees [Clark, 1964, 1976; Schweickert, 1978, 1981].

The Late Jurassic Nevadan orogeny, a prominent event throughout much of the western Sierra Nevada, is the only regional orogenic event that affected the Mesozoic rocks west of the Melones and Sonora faults [Clark, 1964; Schweickert, 1978, 1981; Schweickert et al., 1984]. Older sets of structures have been noted in the northern Sierra Nevada east of the Melones fault [Schmidt, 1982; Schweickert et al., 1984], but the Nevadan folds control the outcrop pattern and orientation of cleavages [Taliaferro, 1942; McMath, 1966; Bateman and Wahrhaftig, 1966]. The only part of the western metamorphic belt not greatly affected by the Nevadan orogeny is that part east of the Melones and Sonora faults, south of 39°N [Schweickert et al., 1984]. This region is underlain by the Calaveras and Shoo Fly complexes, which were penetratively deformed and metamorphosed to greenschist facies and higher before the Nevadan orogeny, as shown by radiometric dates on crosscutting plutons compiled by Schweickert et al. [1984]. Thus these metamorphic complexes had been fully incorporated into the continental crust of North America before Late Jurassic time.

The Nevadan orogeny is known to have occurred in Kimmeridgian time because the lower Kimmeridgian Mariposa Formation, the youngest bedrock in the region, is tightly folded and this set of folds is cut by plutons as old as 154 Ma (Kimmeridgian, according to Armstrong [1978] and Schweickert et al. [1984]). These data constrain the Nevadan orogeny to a very short span of time, shorter than the Kimmeridgian Age which is estimated to represent 2-4 Ma [van Hinte, 1978]. We estimate the age of the Nevadan orogeny to be 153 ± 3 Ma based on data compiled by Schweickert et al. [1984].

The Melones and Sonora faults were active for an unknown length of time before the Nevadan orogeny and ceased major movements afterward, when tectonic activity shifted westward to a subduction zone at the site of the Franciscan Complex [Dickinson, 1981]. The Melones fault has long been considered a major stratigraphic and structural boundary and more recently, a probable ancient plate boundary, but its direction of offset and interpretation remain controversial. Blueschist facies rocks of Middle Jurassic age or older within the northern part of the Melones fault zone (Figure 1) suggest that subduction occurred during or prior to Middle Jurassic time, but the full time span of subduction is not known [Schweickert et al., 1980]; strike slip may have occurred at other times. In the following, we present evidence for reverse faulting, probably in conjunction with subduction, immediately before or during the Nevadan orogeny.

All samples were cored in the field with a portable gasoline-powered drill and oriented with a magnetic compass. The sampling localities are distributed in three well-dated formations the locations of which are given in Table 1 and Figure 1. More detailed maps are also available (Bogen, 1983).

The northernmost sampling sites are in the

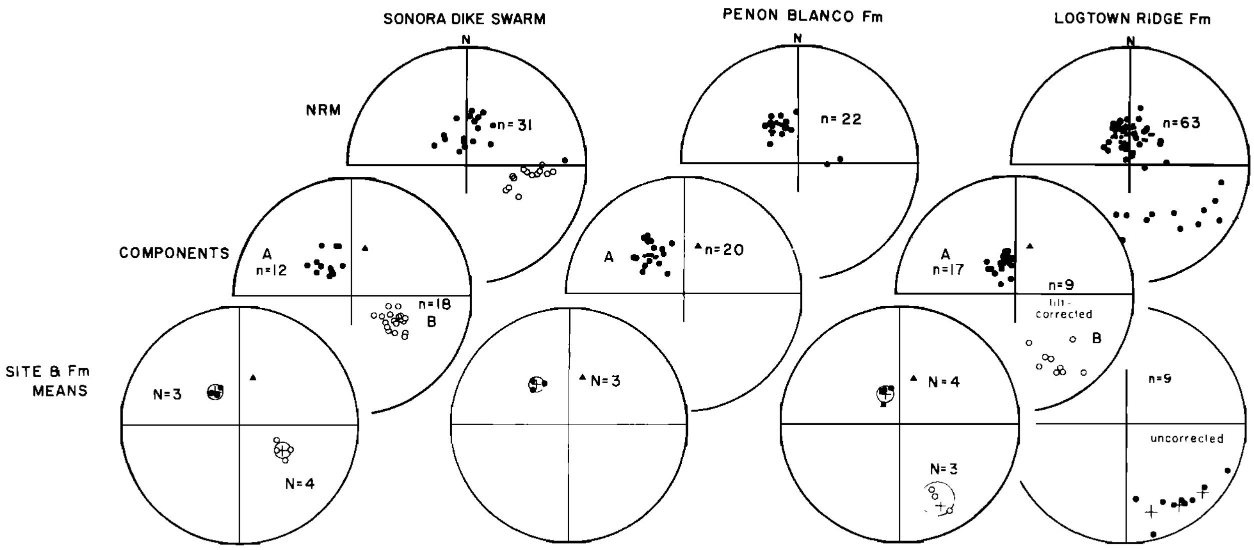

Fig. 2. Paleomagnetic data from the western Sierra Nevada on equal-area, polar projections. Solid (open) circles are on the lower (upper) hemisphere; the triangle represents the present field at the sampling sites. Crosses give the formation means. Two groups of directions are present in both the natural remnant magnetizations and the demagnetized data, a northwesterly, normal group and a southeasterly, reversed group. Data from the Logtown Ridge Formation are shown with and without tilt correction. Data points vary in size for clarity.

type section of the Logtown Ridge Formation along the Cosumnes River west of the Melones fault [Duffield and Sharp, 1975]. The Logtown Ridge Formation is a homoclinal, east facing sequence of basaltic pillow lava and pillow breccia, tuffaceous turbidites, and basaltic dikes and sills [Taliaferro, 1942, 1943; Clark, 1964; Duffield and Sharp, 1975]. Each of these lithologies except tuffaceous turbidites was sampled, and 69 samples were collected at 12 sites distributed over a section 1000 m thick. The rocks have undergone low greenschist facies metamorphism; albite, chlorite, and sphene are present, but deformation is minor and the pillows have not been noticeably flattened. The formation contains Callovian ammonites in the lower half and is overlain conformably by the upper Oxfordian-lower Kimmeridgian Mariposa Formation [Imlay, 1961; Duffield and Sharp, 1975]. Sites JLA-JLC are Callovian or Oxfordian in age, probably the latter, and sites JLD-JLM are Callovian.

Eighty kilometers to the south-southeast of the Logtown Ridge sites (Figure 1), west facing exposures of the Penon Blanco Formation occur within a few hundred meters of the Melones fault. The exposures consist of variably foliated, flattened, and partially recrystallized pillow lava, probably basaltic. Twenty samples were taken from three sites on Woods Creek [Bogen, 1983]. The age of the Penon Blanco Formation is early Jurassic (180-200 Ma) based on radiometric dates [Morgan, 1976; Saleeby, 1982].

A third suite of samples (32 samples from six sites) was collected from the Sonora dike swarm, an extensive swarm of east-northeast striking diabase dikes that intrudes the metamorphosed Calaveras and Shoo Fly complexes and the Standard pluton east of the Sonora fault [Schweickert, 1981; Schweickert and Bogen, 1983]. Six dikes were sampled from a region extending approximately 4.5 km north-south and 2 km east-west. The dikes are not noticeably foliated in hand sample or thin section but do show minor evidence of low-grade metamorphism such as rare sphene and leucoxene and minor chlorite and epidote. Plagioclase laths are probably albitized. One of the dikes sampled yielded 157-159 Ma K-Ar hornblende ages [Sharp, 1980] and we assume that these ages approximate that of the swarm. The ages correspond to the Oxfordian Stage according to Armstrong [1978] and thus the Sonora dikes are approximately the same age as rocks in the upper part of the Logtown Ridge Formation.

Paleomagnetic Methods and Analyses

Natural Remnant Magnetizations

The direction and intensity of the natural remnant magnetization (NRM) of each of 121 samples was measured on a computerized spinner magnetometer. Intensities range typically from 0.05 to 0.2 A/m. Samples from the Logtown Ridge Formation showed the greatest varition in intensity (7×10^{-3} to 6.5 A/m); those from the Penon Blanco Formation generally yielded the lowest values (0.01-0.5 A/m) and the Sonora dikes yielded the highest intensities (0.1-13 A/m).

The NRM data show at least two groups of directions with a northwesterly, downward directed component common to all three formations (Figure 2). The Logtown Ridge Formation and the Sonora dikes also yielded southeasterly to easterly magnetizations directed both upward and downward. The southeasterly directions in the Sonora dikes are approximately antipodal to the northwesterly directions and thus appear to be reversed. The southeasterly NRM directions from the Logtown Ridge Formation are not antipodal and show considerable scatter.

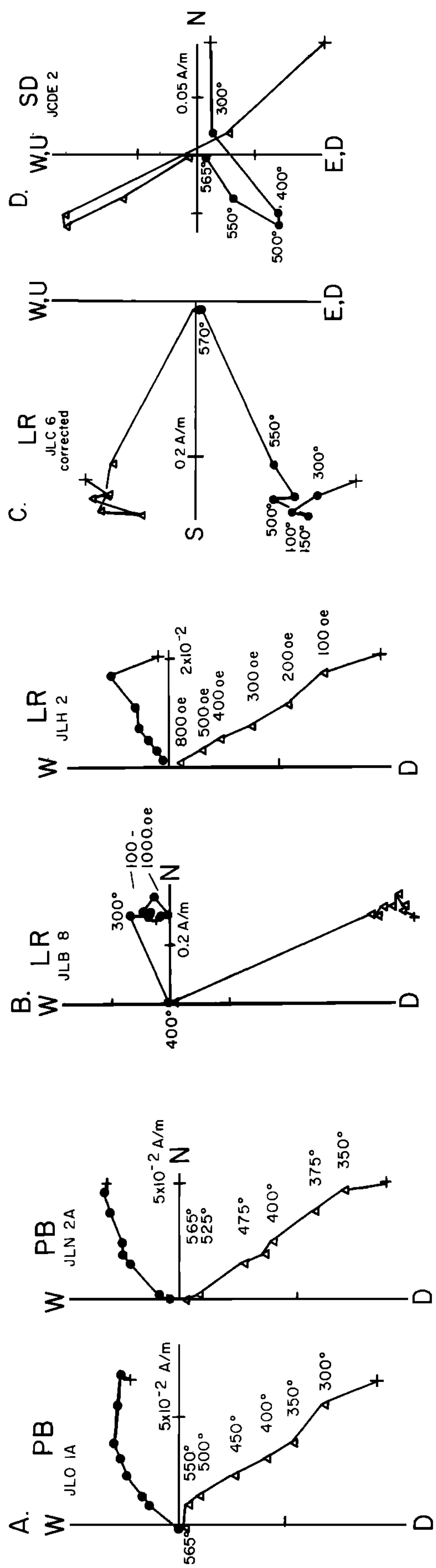

Fig. 3. Vector end point diagrams showing progressive demagnetization of samples from (a) the Penon Blanco Formation, JLO 1A, JLN 2A; (b) Logtown Ridge Formation, JLH 2, JLB 8, and (c) Logtown Ridge Formation, JLC 6 and (d) Sonora dikes, JCDE 2. Circles (triangles) are in the horizontal (vertical) plane, and temperatures are in degrees Celsius. Crosses indicate the NRM direction. Sample JLC 6 has been corrected for the dip of bedding.

Demagnetization Studies

A pilot study using both alternating field and thermal demagnetization techniques showed that thermal treatment is necessary to demagnetize the samples. Treatment in an alternating field did not break down the magnetization in most test samples, as, for example, sample JLB 8 (Figure 3b), or produced anhysteretic or viscous behavior. Thermal demagnetization was carried out in five to eight steps from 200° or 300°C up to 575°C for samples with the highest blocking temperatures (TB). Some magnetizations virtually disappeared near 400°C (JLB 8, Figure 3b).

The magnetization direction of each sample was determined by plotting the demagnetization data on a vector end point diagram [Zijderveld, 1967]. Components of the magnetization are defined by a linear array of vector end points and the orientation of each component was determined by regression analysis. Typical examples from each formation are shown in Figure 3. Samples that failed to yield a clear linear trend in the demagnetization data were rejected. Samples from five sites in the lower part of the Logtown Ridge Formation yielded no linear trends, and these sites were rejected (JLD, JLE, JLF, JLG, JLM). In averaging the sample directions, we have followed the hierarchical scheme suggested by Irving [1964]. Individual sample directions were averaged as unit vectors to obtain site mean directions (Table 1). Site means were averaged similarly to remove the effects of secular variation and to obtain formation means (Table 2) without obscuring variations between sites, which may be significant, particularly in deformed rocks.

Analysis of Northwesterly Directions

Penon Blanco Formation. The demagnetization data from the Penon Blanco Formation show northerly directions up to about 400°, probably representing the present field (JLN 2A, Figure 3a). Above that temperature all samples yielded magnetizations directed downward to the northwest (Figure 3a) up to 565°C, indicating that the carrier is magnetite. None of the Penon Blanco samples were rejected.

The demagnetization data from the Penon Blanco formation yield results for 20 samples of D = 322.6°, I = 53.2°, and α_{95} = 5.2° (Figure 2 and Table 2). The formation has been folded at the sampling sites and a fold test [Graham, 1949; McElhinny, 1964] shows that the magnetization postdates the Kimmeridgian structure. Thus the northwesterly direction is a secondary magnetization.

Logtown Ridge Formation. The demagnetization data from the Logtown Ridge Formation show two groups of directions or components. Most common is the northwesterly direction (component A), as in sample JLH 2 (Figure 3). This direction dominates the data from four sites (JLA, JLB, JLH, JLJ; Table 1) and shows a broad TB spectrum up to a maximum of 575°C, indicating that the carrier is probably magnetite. The other three sites (JLC, JLK, JLL) yield southeasterly, downward directions (component B, Table 1 and Figure 2) typically up to 565°C.

Component A from four sites from the Logtown

TABLE 1. Site Means

Site	R_s	In Situ D	In Situ I	In Situ k	In Situ α_{95}	Corrected for Tilt D	Corrected for Tilt I	Corrected for Tilt K	Corrected for Tilt α_{95}	S/D,deg
			Logtown Ridge Formation (38° 32.95'N 120° 51.00'W)							
JLA	4/5	348.8	62.7	236	4.6	52.6	-2.1	236	4.6	170/93
JLB	8/8	333.4	62.8	35	8.4	53.9	4.8	35	8.4	170/93
JLC	4/6	132.1	14.0	34	12.0	155.0	-39.3	39	11.2	170/93
JLH	4/7	336.7	60.7	108	7.8	66.0	14.3	108	7.8	3/88
JLJ	4/5	320.9	72.9	115	6.5	75.3	10.4	115	6.5	359/90
JLK	2/5	147.0	17.5	---	---	155.0	-30.7	---	---	359/90
JLL	3/5	164.3	21.2	18	19.2	151.2	-17.0	29	15.0	359/90
			Penon Blanco Formation (37° 54.75'N 120° 25.90'W)							
JLN	6/6	317.0	55.0	299	3.3	118.1	1.3	299	3.3	215/123
JLO	6/6	321.3	49.0	83	6.3	354.8	10.6	83	6.3	125/90
JLP	8/8	329.8	55.1	48	7.1	111.1	-0.6	48	7.1	215/123
			Sonora Dikes (37° 59.75'N 120° 22.05'W)							
JCDA	4/6	324.7	61.6	41	10.9					
JCDB	5/5	112.9	-63.2	122	5.7					
JCDC	6/6	117.6	-51.3	114	5.4					
JCDD	4/5	126.0	-59.4	6	8.6					
JCDE	3/5	128.9	-50.0	217	4.7					
JCDE	4/5	315.6	59.5	93	7.3					
JCDF	4/6	332.5	58.5	44	10.5					

R_s is the ratio of the number of samples averaged to the number collected at each site. D, I are declination and inclination. k, α_{95} are the statistical parameters of Fisher [1953]. S/D is the strike and dip of bedding. The dip direction is clockwise 90° from the strike.

Ridge Formation with northwesterly directions has an average orientation of D = 336.4°, I = 65.3°, and α_{95} = 6.1° (Figure 2 and Table 2). A conglomerate test on pillow breccia at site JLB yielded consistent northwesterly directions for seven of eight pillow fragments, indicating that component A is secondary and formed after brecciation of the pillow lava.

Sonora dikes. The Sonora dikes also yielded two sets of magnetization directions. A northerly or northwesterly, downward directed component is present to 400-500°C in most samples as, for example, JCDE 2 (Figure 3d). The data also define a southeasterly, upward directed component that decays to the origin between 500° and 565°C in most samples (Figures 2 and 3d), probably carried by magnetite. These data show that the remnant magnetization of the Sonora dikes contains two components: component A, a northwesterly, downward directed component of intermediate to high blocking temperature (400°-565°C) and component B, a southeasterly, upward directed component with a higer blocking temperature spectrum (500°-565°C).

Component A of the Sonora dikes has an average orientation of D = 320.1°, I = 49.1°, and α_{95} = 7.7° (Figure 2 and Table 2). No field tests are available to bracket the age of this magnetization, but the fact that a component of higher TB is present suggests that the northwesterly directions are secondary like those of the other two formations.

Analysis of Southeasterly Directions

The Logtown Ridge Formation and the Sonora dikes both yielded southeasterly magnetizations (component B) with moderate to high (500°-565°C) TB spectra. Southeasterly, upward directed magnetizations occur in 18 samples of four of the Sonora dikes and produce a formation mean of D = 121.8°, I = -56.1°, and α_{95} = 6.5° (Figure 2 and Table 2). These directions are approximately antipodal to the northwesterly, secondary directions shown in Figure 2 and the demagnetization diagram of sample JCDE 2 (Figure 3d). The higher TB of this component compared with component A suggests that it is the characteristic magnetization [Zijderveld, 1967] of the Sonora dikes. It is not clear, however, that secular variation has been averaged out completely judging by the moderately high value of the precision parameter (115), yet it seems unlikely that all the dikes sampled were intruded and cooled within a few thousand years.

The southeasterly magnetizations from three sites in the Logtown Ridge Formation are similar to those of the Sonora dikes in declination but are directed downward rather than upward and show more scatter. The directions appear to be arrayed in a partial small-circle girdle (Figure 2), which suggests folding. Nine samples from three sites yielded an average D = 147.6°, I = 17.9° with α_{95} = 15.7°; if a correction for the tilt of bedding is applied, then D = 153.9°, I = -29.0°, with α_{95} = 11.3° (Table 2). The tilt correction reduces the diameter of the circle of 95% confidence slightly and appears to eliminate the small-circle girdle, but the correction is not significant at the 95% confidence level because there is little variation in the attitude of bedding among the three sites. The tilt correction, however, does move the formation mean into the same octant as component B of the Sonora

TABLE 2. Formation Vector Means and Paleomagnetic Pole Positions.

	R_s	D	I	k	α_{95}	λ',deg	ϕ',deg	dm	dp
Logtown Ridge Formation									
Component A	4/12	336.4	65.3	132	6.1	70.5N	182.6E	10.0	9.0
Component B									
Tilt corrected	3/12	153.9	29.0	51	11.3	57.6N	111.oE	11.9	6.2
Uncorrected	3/12	147.6	17.9	26.5	15.7	33.7S	278.5E	16.3	8.5
Sonora dike swarm									
Component A	3/6	324.3	60.0	313	4.6	62.6N	165.4E	7.0	5.3
Component B	4/6	121.8	-56.1	115	6.5	44.5N	166.3E	9.3	6.7
Penon Blanco Formation									
Component A	3/3	322.6	53.2	240	5.2	59.1N	153.8E	7.8	5.6
Kimmeridgian Sierran Pole Positions									
Three formation average (Component A)				93	8.4	64.5N	165.2E		
Five formation average			93	6.5	67.2N	161.2E			
Sonora dike swarm									
Tilt corrected		151	-43			62.5N	130.1E		

R_s is the ratio of sites averaged to those collected; D, I, k $\alpha(A)_{95}$ are as in Table 1; ', ' is the latitude and longitude respectively of the paleopoles; dm and dp are the semiangles of the axes of the oval of 95% confidence about the poles. Three formation average and five formation average refer, respectively, to the average pole positions calculated from the three Kimmeridgian (component A) formation means given herein and those three means combined with two given by Hannah and Verosub [1980].

dikes and opposite the octant containing component A (Figures 2 and 3c). This suggests that component B from the Logtown Ridge Formation may be characteristic and that the tilt correction is warranted.

Of the three reversed site means determined from component B of the Logtown Ridge Formation (Figure 2 and JLC, JLK, JLL in Table 1), one differs considerably in paleoinclination from the other two and therefore the formation mean has a large semiangle (11.3°) of the cone of 95% confidence. Site JLC, 200 m below the top of the formation, shows the steepest inclination (-39°) and is also the highest stratigraphically among the three sites. Sites JLK and JLL are located approximately 650 m below the top of the formation and are only about 6 m apart but show lower inclinations of -31° and -17°, respectively. Rejection of site JLL with its low paleoinclination would reduce the circle of 95% confidence about the formation mean to 6.9°, but its statistical significance would be doubtful. Five other sites in the Logtown Ridge Formation were rejected for failure to yield reproducible magnetizations and are all located more than 650 m below the top of the formation. Thus it appears that the paleomagnetic data are progressively less reliable downsection. Elevated temperatures deep in the volcanic pile, accompanied by frequent field reversals, may have partially or completely destroyed these magnetizations.

Ages of the Magnetizations

The ages of the magnetizations are not bracketed completely but may be inferred with reasonble confidence. Component A is present in each of the three formations despite their different ages. The magnetization postdates both brecciation of the Logtown Ridge pillow lavas and Nevadan folding of the Penon Blanco Formation. Component A therefore is probably related to Nevadan metamorphism in the latter part of Kimmeridgian time. This is supported by the fact that the Penon Blanco Formation, which is cleaved and partially metamorphosed to low-greenschist facies at the sampling sites, yielded only northwesterly, secondary magnetizations. Because the structural-metamorphic fabric cuts the folded bedding, its final stages of development postdate the folding. In contrast, the Sonora dikes and Logtown Ridge samples lack a metamorphic fabric and yield two magnetic components. Thus we consider it likely that component A is due to Nevadan metamorphism of all three formations in the latter part of Kimmeridgian time. No younger metamorphic event is known to have affected the rocks at these localities and plutons of the Sierra Nevada batholith are 20-90 km distant from the sampling sites. If these plutons, which range in age from Late Jurassic to Late Cretaceous, were responsible for the remagnetization, then we would expect a distribution of poles streaked toward the Cretaceous reference pole, reflecting some 65 Ma over which the batholith developed.

The Logtown Ridge Formation contains a component of higher coercivity than the Nevadan magnetization (component A), but this component is not reversed unless corrected for tilting due to the folding. If the higher-coercivity magnetization directions were younger than component A, then major post-Jurassic displacement relative to North America would be implied, since this direction yields a pole position far from those of post-Jurassic North America (Table 2). This seems highly unlikely, however, because there is little or no evidence to suggest that the Logtown Ridge Formation has been translated or deformed since the Nevadan orogeny. In addition, the partial small-circle girdle defined by component B is removed by the tilt correction, and the correction therefore seems warranted. This implies that component B predates folding and is probably primary or nearly so and therefore is Callovian or Oxfordian in age.

Reversed magnetizations (component B) from the Sonora dikes have directions similar to the tilt-corrected directions from the Logtown Ridge Formation and approximately antipodal to the northwesterly, secondary magnetizations (Figure 2). These relationshis suggest that the component B from the Sonora dikes may be primary and of Oxfordian age. Numerous reversals of the earth's magnetic field occurred during Late Jurassic time [Steiner and Helsley, 1975a, b; Steiner, 1980], and therefore both the normal and reversed components could be of Late Jurassic age. We conlude that all of the higher TB magnetizations determined herein are of Late Jurassic age; the secondary normal magnetization formed during the Kimmeridgian Age and the reversed magnetizations are approximately Oxfordian, about one age older.

Discussion

The demagnetization data show that the northwesterly, secondary magnetization is present in each of the three formations sampled. Secondary magnetizations with similar orienations occur in the Devonian or Mississippian Taylor and Permian Reeve formations, about 125 km north of our northernmost sampling locality (Figure 1), in an area of more intense Nevadan deformation [Hannah and Verosub, 1980]. Hannah and Verosub [1980] concluded that these magnetizations are of Late Jurassic age and resulted from the Nevadan orogeny. Thus evidence of the Kimmeridgian magnetization has come from five widely spaced formations in the Sierra Nevada metamorphic belt. This magnetization is most likely the result of widespread rerystallization of magnetite during low-greenschist facies metamorphism that accompanied the Nevadan orogeny. We suggest that the northwesterly magnetization may be a paleoagneitc "signature" of the orogeny and an indicator of the areal extend of metamorphism.

The reversed magnetizations in the Logtown Ridge Formation and Sonora dikes presumably reflect a geomagnetic field reversal during the Oxfordian or Kimmeridgian ages. Steiner and Helsley [1975a,b] and Steiner [1980] have shown that numerous field reversals occurred during Late Jurassic time, but because each of their polarity intervals is much shorter than an age, we are unable to correlate the reversal(s) in our data with any specific reversal shown by them. It also is unlikely that our normal and reversed magnetizations represent consecutive polarity intervals, considering the frequency of field reversals during Late Jurassic time. Furthermore, the reversed magnetizations in the Logtown Ridge Formation and Sonora dikes need not represent the same polarity interval.

Paleomagneitc Pole Positions and Implications for Displacement of Sierran Rocks

Pole positions calculated from the formation mean directions (Table 2) for both normal reversed polarities are shown in Figure 4 together with Jurassic and Cretaceous poles from the North American craton. The North American poles (listed in the caption to Figure 4) are based on well-grouped data from thermally demagnetized samples and are similar to those shown by Smith and Noltimier [1979] for the Jurassic-Triassic. The two Cretaceous poles are averaged from data given by McElhinny [1973]. Three Kimmeridgian Sierran poles based on the northwesterly, Nevadan magnetizations reported herein plot close to the two Kimmeridgian pole positions (Figure 4a, poles 4 and 5) for the Morrison Formation in Utah [Steiner and Helsley, 1975a]. The mean of three new Sierran poles (see Table 2, not shown on Figure 4a) falls between the two Morrison Formation poles. Thus there is an excellent correspondence between our Kimmeridgian poles and those for North America.

Post-Jurassic Movement the Sierra Nevada

The close correspondence between the mean Sierran pole position and that of coeval North America allows only small movements of the region with respect to North America since Late Jurassic time [Bogen et al., 1983]. Beck [1980] and Demarest [1983] have discussed methods of calculating the magnitude of tectonic movements at the 95% confidence level from paleomagnetic data. Using their method, we find that rotation of the Sierra Nevada block about a vertical axis is $2.5° \pm 8°$ at the 95% confidence level. Similarly, the flattening or rotation about a horizontal axis is $0.8° \pm 4.4°$. Thus the paleomagnetic data indicate little or no large-scale relative movement since the Nevadan orogeny. Cretaceous paleomagnetic poles from the Great Valley Group and Sierra Nevada batholith also suggest little or no movement since that time [Gromme and Merrill, 1965, Gromme et al., 1967; Mankinen, 1978; Frei et al., 1984]. The close correspondence between results described herein and those from plutons and unmetamorphosed sedimentary rocks indicates that stable secondary magnetizations of metavolcanic rocks area good indicator of subsequent tectonic movements.

Reversed Magnetizations

Pole positions for the reversed formation means (component B) from the Logtown Ridge Formation and Sonora dikes are shown in Figure

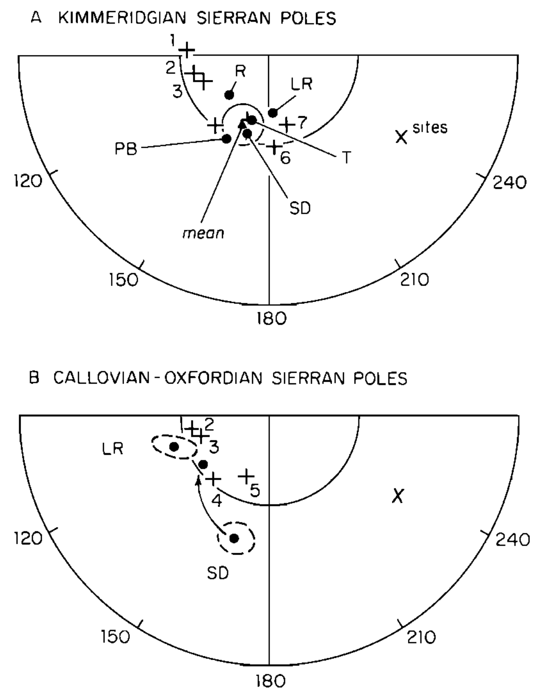

Fig. 4. Paleomagnetic pole positions shown on north-polar, equal-area projections. (a) Nevadan poles (circles) based on secondary magnetization of five formations in the western Sierra Nevada and their mean (triangle). R, T are poles from the Reeve and Taylor formations [Hannah and Verosub, 1980]; LR and PB are the Logtown Ridge and Penon Blanco formations, and SD indicates the Sonora dike swarm. The circle of 95% confidence about the mean pole (triangle) includes the Kimmeridgian pole from the upper part of the Morrison Formation (cross 5). The other North American reference poles (crosses) range from Early Jurassic (1) to Late Cretaceous (7). (b) Poles from reversed formation means for the Logtown Ridge Formation (LR) and Sonora dike swarm (SD). The arrow indicates the restoration of the Oxfordian pole from the Sonora dikes into the approximate region of the Oxfordian pole position of North America between the Callovian Summerville Formation pole (3) and the two Kimmeridgian Morrison Formation poles (4 and 5). The restoration involves a simple tilt correction of 27° toward the south-southwest about a horizontal axis trending 295°. See text for discussion. Reference poles for North America: 1, group 1 dikes, Early Jurassic (190 Ma); 2, group 2 dikes, Middle Jurassic (175 Ma [Smith and Noltimier, 1979]); 3, Callovian Summerville Formation, Middle Jurassic [Steiner, 1978]; 4 and 5, lower and upper Morrison Formation, Kimmeridgian to Early Tithonian [Steiner and Helsley, 1975a]; 6 and 7, Early and Late Cretaceous average poles based on data given by McElhinny [1973].

4b. Neither pole is close to the Morrison Formation poles (4 and 5), although the age difference between the two is only a few million years. The pole position for the reversed formation mean from the Logtown Ridge Formation lies near the Callovian (3) and Middle Jurassic (2) pole positions for stable North America [Steiner, 1978; Smith and Noltimier, 1979]. This is due primarily to the low paleoinclination at site JLL. If site JLL were rejected, the pole for the Logtown Ridge Formation would lie between the Callovian and Kimmeridgian poles (3 and 4, respectively), as expected from its probable Oxfordian age. The maximum age of these magnetizations is Callovian (approximately 165 Ma [Armstrong, 1978]), although an Oxfordian age is more likely.

The Nevadan orogeny occurred in the Kimmeridgian (approximately 153 Ma), which allows a maximum of about 10 Ma between extrusion of the Logtown Ridge Formation and the orogenic event. Northward movement of 10 cm/yr for 10 Ma would be equivalent to a change in paleolatitude of 10°, which is smaller than the major semiangle of the cone of 95% confidence about the Logtown Ridge pole. Thus the imprecision of the data permits, but does not demand, northward transport. If site JLL were rejected, however, much less northward transport would be allowed due to the reduced size of the oval of 95% confidence and its coincidence with the apparent Oxfordian pole position for North America. In addition, the paleodeclination of the Logtown Ridge Formation indicates little or no rotation since Oxfordian time.

The wall rocks of the Sonora dikes were deformed, metamorphosed and incorporated into the North American continental crust before Late Jurassic time, and therefore North America pole positions are to be expected for primary magnetizations from the dikes if they have not undergone Nevadan deformation. Thus the pre-Nevadan magnetization may be used as a structural marker of known original orientation. The orientation of the dikes is 080°, approximately perpendicular to the direction of Nevadan shortening, and therefore the dikes probably are sensitive to large-scale rotations but not to mesoscopic folding. A discrepancy between the pole positions of the Sonora dikes and those of North America must be due to rotation of the sites during Late Jurassic deformation, and the magnitude of the discrepancy should be equal to the amount of tectonic rotation.

The Oxfordian pole position for North America is not known but almost certainly falls between the poles of Middle Jurassic (2 and 3) and Kimmeridgian (4 and 5) age shown in Figure 4. The Oxfordian pole for the Sonora dikes may be moved into this intermediate area by a simple tilt correction of 25°-30° toward the south-southwest about a horizontal axis trending between 285° and 305°. This rotation is geologically realistic because major Nevadan fold axes in Jurassic rocks nearby are subhorizontal and are subparallel to the Sonora fault, which strikes between 285° and 330° [Eric et al., 1955; Clark, 1960]. These data suggest that rocks east of the Sonora fault (including the Sonora dikes) were deformed about similar structures, and thus we consider 25°-30° to be a good estimate of the tectonic rotation of the dikes about a horizontal axis immediately prior to or during the Nevadan orogeny. Other, more complicated rotation schemes are not ruled out by these data, but this hypothesis is the simplest and is in accord with our understanding of the structural history of the region.

Melones and Sonora Faults

In the analysis of the paleomagnetic data, we have shown that structural corrections are warranted for the characteristic magnetizations measured in both the Logtown Ridge Formation and the Sonora dikes. The Logtown Ridge Formation lies west of the Melones fault, and the Sonora dikes are east of both the Melones and Sonora faults, although the two units are separated by some 80 km along strike (Figure 1). A third structural block consisting of phyllite and greenschist of Jurassic age lies between the two faults. Bedding in the Logtown Ridge Formation has been rotated eastward to a subvertical orientation by folds and faults trending about 350°. On the east side of the Sonora fault, however, the Sonora dikes have apparently been rotated only 25°-30° eastward about a horizontal axis trending approximately 300° (Figure 5). These differential rotations are a measure of the contrast in large-scale, rigid body rotations that developed across the faults during the Nevadan orogeny.

The existence of a contrast in finite strain across the Melones and Sonora faults was suggested by Schweickert et al. [1984] because the prominent Nevadan cleavages and folds to the west of the Sonora fault are represented by weakly developed crenulation cleavages and local mesoscopic folds to the east of the fault. The amount of rotation indicated by the paleomagnetic data is also smaller to the east of the faults. Schweickert et al. [1984] suggested that the contrast in strain across the faults is the result of the different structural and metamorphic histories of the wall rocks. The eastern wall rocks (the Calaveras and Shoo Fly complexes) were deformed and metamorphosed to greenschist facies and higher at least twice prior to the Late Jurassic Nevadan orogeny [Schweickert, 1981]. These tectonized units were incorporated into the continental crust before Late Jurassic time and responded to Nevadan deformation like nearly rigid basement. In contrast, the Jurassic units west of the Sonora fault were tightly folded, cleaved, and metamorphosed for the first time during the Nevadan orogeny. This fundamental difference in structural properties may account for the major contrast in finite strain across the faults and for the differential rotations inferred from the paleomagnetic data.

The original orientations of the Melones and Sonora faults have been a matter of speculation because no useful structural markers have been identified previously in the eastern wall rocks. The Sonora dikes, as noted previously, are oriented about 080° and vertical, subperpendicular to known Nevadan folds, and thus are not sensitive to local tilts resulting from mesocopic folding about northernly or northwesterly fold axes. The paleomagnetic evidence of rotation of the Sonora dikes applies also to their host wall rocks. Because the wall rocks west of the northern Melones fault and east of the Sonora fault (Figure 1) both underwent tectonic rotation, the implication is that the faults have been rotated by an amount equivalent to that of the Sonora dikes. According to this hypothesis, the northern Melones and Sonora faults would have originally dipped 50°-60° east,

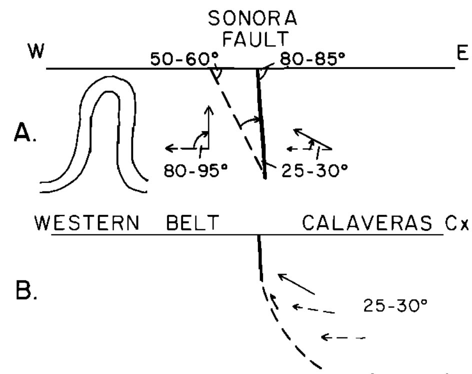

Fig. 5. Schematic cross section of the Sonora fault. The western wall rocks, including the Logtown Ridge and Penon Blanco formations have been tilted 80°-95°, on average, about subhorizontal axes during Nevadan folding. The eastern wall rocks, including the Sonora dike swarm, have been tilted 25°-30°, as indicated by the paleomagnetic data. (a) The fault is rotated together with the eastern wll rocks from a previous dip of 50°-60°E. (b) Alternatively, the fault is less steep at depth than at the surface causing the rotation of the eastern wall rocks during reverse slip.

25°-30° less than their present 80°-85° eastward dip (Figure 5a). Although our results do not apply rigorously to the southern part of the Melones fault, we assume from its parallelism with the Sonora fault that it originally may have had a similar 50°-60° eastward dip. This result contradicts both the hypothesis that the Melones fault is a folded thrust south of 39°N [Taliaferro, 1943] and the idea that the faults were subvertical features during Late Jurassic time, as they are at present.

The rotation of the eastern wall rocks of the Melones and Sonora faults could have occurred without rotation of the faults themselves if their dips decrease with depth (Figure 5b). In this case, reverse movements would be required to produce the measured rotation of the eastern wall rocks. However, this hypothesis seems less attractive than the previous because it does not link the measured rotations directly to Nevadan folding. Yet both models indicate that the Melones and Sonora faults flatten at depth and were probably reverse faults during Late Jurassic time. The recently acquired COCORP line across the northern Sierra Nevada should provide a critical test of this aspect of our hypothesis. In addition, the tilting of the Sonora dikes and their wall rocks might be expected to have resulted in substantial uplift. Uplift of the hanging wall during the Nevadan orogeny has been demonstrated from the stratigraphy and sedimentary petrology of the footwall rocks [Bogen, 1984]. Thus our hypothesis concerning the tilting is supported by independent data and is further testable by seismic reflection profiling.

Conclusions

Paleomagnetic studies of Jurassic rocks west of the Melones fault and east of the Sonora fault yield two distinct groups of magnetizations. A northwesterly, normal magnetization present in each of three formations studied is a secondary magnetization related to metamorphism during the Nevadan orogeny. We conclude that this nearly ubiquitous magnetization constitutes a paleomagnetic indictor of the spatial extend of Nevadan metamorphism. An antipodal group is present only in the two Upper Jurassic formations sampled and probably is primary or nearly so because it predates folding.

Paleomagnetic pole positions derived from the secondary magnetizations correspond closely with those of Kimmeridgian North America and indicate that the net post-Jurassic rotation of the Sierra Nevada block has been quite small (2.5°±8°) and that tilting or north-south transport has been negligible. The close correspondence of these results with those from Cretaceous rocks shows clearly that secondary magnetizations of metamorphic rocks can yield valid, useful data. Similar data may prove useful elsewhere, as well, in regions where primary magnetizations are absent or difficult to demonstrate.

Characteristic, reversed magnetizations of high TB spectra identified in samples of the Sonora dikes are almost certainly primary since the dikes are only about 5±3 Ma older than the Nevadan orogeny. The dikes are considered part of Late Jurassic North America, and the discrepancy between their pole position and that of late Jurassic North America is attributed to a 25°-30° tilt about horizontal axes during the Nevadan deformation. This is consistent with structural evidence in that the eastern wall rocks were not greatly deformed during the Nevadan orogeny and also implies that the faults were originally moderately steep reverse faults not rotated thrusts or subvertical faults. These conclusions appear to apply south of 39°N where polyphase-deformed and metamorphosed rocks of the Calaveras and Shoo Fly complexes compose the hanging wall of the Sonora fault. These units behaved like nearly rigid basement, in contrast to the Jurassic rocks west of the Melones fault, which underwent rotations of as much as 93° due to folding and faulting. An alternative interpretation is that the eastern wallrocks rotated during reverse slip on faults that flatten with depth.

We conclude that these interpretations are consistent wih other geologic evidence, particularly the blueschist-facies rocks in the fault zone, which suggest that the Melones and Sonora faults were dip-slip faults within a steep subduction zone immediately prior to and during the Nevadan orogeny.

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